A MULTI-DOMAIN MODEL FOR PRODUCT AND MANUFACTURING SYSTEM DESIGN

A Thesis

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Dedication

I would like to dedicate this to my parents, brother and my friends for their continuous support throughout my student as well as professional life.

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Abstract

The present work is shown to bring two different domains which are manufacturing and design into picture and to make them co-exist with one another. The increase in customer diversity and variety in demand has led to the proliferation of product variety to the point of mass customization and personalization which also changed the product design constantly. These rapid changes are handled with the help of matrices Design Structure Matrix (DSM) and Incidence Matrix (IM) which help to understand how the machines and parts and components of parts interact with each other.

The DSM shows how the component of parts and arranged in a module and the IM shows how the parts and machines interact with each other in a cell. The modules and cells help to make the overall process easier by giving a clear representation of their positions and activities. These two modules and cells, when combined makes for a much more efficient understanding of the overall entire process that goes into making a final product.

In literature, there are ways and methods on how the DSM and IM can be clustered to get the best arrangement of the parts and their corresponding machines as well as the components of the parts. However, the current paper aims to combine the two domains together. This is done with the help of Genetic Algorithm (GA). Genetic Algorithm makes use of natural selection to get the best output which helps to bring the two matrices together so that both of them are clustered at the same time to get the final result.

The objective is to develop a new model which can cluster both IM and DSM at the same time. A product module can be manufactured and assembled in a single machine cell. This will make it easier to change, upgrade and manufacture a product, by only modifying specific modules and their corresponding machine cells, without disturbing either the whole product design or the whole manufacturing system.

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List of Abbreviations

F is the summation of clustering results from both DSM and IM.

F_1 is the number of the '1' elements outside clusters (modules or cells).

F_0 is the number of '0' elements inside clusters (modules or cells).

w_1 is the arbitrary weight of the design domain.

w_2 is the arbitrary weight of the system domain.

P_1: Permutation matrix to arrange parts in the original DSM and IM into DSM_{new} and IM_{new}. P_1 is a binary matrix.

P_2: Permutation matrix to arrange machines in the original IM into IM_{new}. P_2 is a binary matrix.

V: Clustering vector to modularize DSM_{new} and IM_{new}. V is a binary vector.

H: Clustering vector to partition IM_{new}. H is a binary vector.

N_M: Number of produced product modules.

N_C: Number of produced machine cells.

CHAPTER 1

INTRODUCTION

1.1 Thesis Statement

This research integrates manufacturing system synthesis with product design by combining the clustering process of the Incidence Matrix (IM) of the manufacturing system and the Design Structure Matrix (DSM) of the corresponding product architecture. This will allow the production of each product module in a separate machine cell and maximize the benefits of design modularity and cellular manufacturing simultaneously.

1.2 Motivation

There are numerous techniques and procedures to manufacture a certain product or part. But there are many different theories and methodologies that help in improving the present techniques for a better outcome. These methodologies range from the slightest change in the placement of a machine to the remodeling of an entire work floor in an industry. In particular, there have been much advancement in how a particular part can be manufactured and many a theory also surrounding that. In addition to this, there is also the process of manufacturing a product that consists of many parts. In literature, we find that there are many approaches and algorithms that help in making the manufacture of parts and products easier and more efficient individually but there has not been a solution so far where the combination of the production of a product and its corresponding parts can be done simultaneously with more efficient techniques. These processes are represented in the form of matrices known as the Design Structure Matrix (DSM) and the Incidence Matrix (IM). The DSM helps in grouping the modules of a part and the IM helps in grouping the cells of product. To manufacture the final product, the modules of a part and the cells of a product have to be clustered using an algorithm in such a way that both of them have efficient outcomes and the whole process combined is taking place in less time than when clustered individually. Such a clustering algorithm not only will help give a better understanding of the various interactions between product components and the process flow and routings, but also a better integration of the cellular structure of the manufacturing system with the modular architecture of the product. Hence, the goal is to associate the manufacturing system synthesis domain with product design domain in a multi-domain model.

1.3 Thesis Organization

This paper starts off with the detailed information on how the world of manufacturing came into existence. The different types of manufacturing practices are explained in the next chapter and how the increase in the specifications of products has led to the improvements in the manufacturing techniques. Furthermore, the manufacturing techniques in practice are explained and how they are affected by the ever changing needs and demands of the customers. In this chapter, the different techniques to produce a product such as Group Technology, Cellular Manufacturing and Production Flow Analysis are discussed. The solution to manufacturing a product consisting of different machines is presented with the Incidence Matrix.

Next, the product design domain shows how a product is made right from the initial stages and how the design is managed and analyzed with the theory of Modular Product Architecture. This talks about how the modules of a product can be arranged in the best possible way to create a product. The chapter ends with what is lacking in literature and how the gap can be addressed.

CHAPTER 2

LITERATURE SURVEY

2.1 Manufacturing Systems Structure and Design

Literature survey gives information related to the theory of manufacturing, how manufacturing has started and its significance. It explains the different types of techniques used over the years and how it has evolved over time in terms of customers' demands and the variety in products. This leads to the topic of group technology which talks about grouping parts based on the similarities and eventually explains about cellular manufacturing where the parts are grouped based on the parts and the part families. A type of cellular manufacturing practice is called Production Flow Analysis which is used to group parts together based solely on the type of process that they have to undergo. These techniques help greatly in customizing the final product easily without any extra setup work. The structure of how the machines are placed in relation to the parts that are being produced is represented with the help of an Incidence Matrix. Again, these parts also consist of components and their architecture varies with each individual part. The design and arrangement of the components in a module helps better understand the interactions that exist between them which is explained in the Modular Product Architecture and the Design Structure Matrix. The aim to bridge the gap between the cells and the modules is talked about in the last section under the Research Gap and Opportunities.

2.1.1 The Evolution of Manufacturing Systems

Manufacturing is important to a nation's financial well-being as it provides quality of life for its citizens. From the time that it has started more than two centuries ago, the manufacturing industry has developed through a number of techniques. Initially, before the emergence of high end manufacturing facilities, Craft Production was the norm (Hu, 2013). A customer can get what they requested for but at a very high price as there were no factories or machines.

To overcome these difficulties, a highly practical approach was invented called Mass Production where a large number of products could be manufactured at the same time. Another concept that was introduced at the same time is the assembly line. The way the assembly line is set up is that the parts keep on moving on the assembly line and get assembled at different stations. This method helped in achieving economies of scale by making a number of products at cheaper rates. On the other hand, there was a downside to this technique which was customization. Since the main aim was to achieve numbers in production, the quality has taken a back seat.

This has changed in the late 20th century when Mass Customization was developed. The manufacturing companies came up with a design that allowed them to have the basic design of the product with extra combinations that they prefer the most. This helped in achieving economies of scope with wider varieties available.

Flexible Manufacturing Systems (FMS) (Algeddawy, 2011) was introduced to help in handling the variety in the production. It brings out the best of economies of scale by combining similar parts and designs and offers variety to a certain level and therefore the initial cost for the setup of these manufacturing systems is a little high. It can be explained as having a set number of hardware but flexible software systems to manage the orders. But this is applicable only until that product lies in the preset available designs and machines. It cannot go beyond that scope and the whole system becomes outdated.

The next type of manufacturing system which came was the Reconfigurable Manufacturing System (RMS). This system is very flexible in terms of being able to adapt to the ever changing designs of products and the machines. It is very easy to replace a machine in order to produce something new. It helps to adapt to the changing environment and responds quickly to unexpected changes like machine failure or market demand.

To overcome these types of scenarios and to help in unexpected situations, another type of manufacturing system known as Changeable Manufacturing System has been introduced. In this, the system is equipped to handle any type of sudden changes in the present day and also to any additions that might happen in the future. This system is designed to work only when the future possibilities are evaluated before setting up methodology (Seleim, Azab, & AlGeddawy, 2012).

2.1.2 Group Technology

Group technology can be simply defined as a management philosophy that arranges products and machines with similar designs and characteristics into groups. Initially batch production environment was prevalent in many manufacturing industries. In this methodology, the machines are grouped according to the type of functions they perform and the similarities among them whereas in group technology, the machines are grouped into cells such that each cell performs the manufacturing operations of a particular product. Group technology can be implemented by any factory by following simple steps (Burbidge, 1996).

The first step is to group the machines and parts based on their functionality and similarity. The next step is to change the plant layout to fit the manufacturing cells and operations. The last stage comprises continuous improvement techniques to make the production process better.

There are many advantages to group technology. It helps reduce the setup times, work in process inventory and material handling cost. It helps to increase the quality of the products, material flow and economic usage of factory floor space.

There are different layouts that can be achieved with group technology which are production line layout, functional organization layout and cellular layout (Ribeiro dos Santos & Oliveira de Araújo, 2003). The production line layout has machines setup in such a way that they follow a preset manufacturing operations routine to produce a certain part or group of products. The functional layout is similar to job shop type of production in which machines which are similar in their functionalities are grouped together and the parts are processed through these machines. The cellular layout is equipped with machines that are dedicated to the manufacturing of a particular type of product. The routings are such that they make the best of use time and space and in this way a lot of resources are saved. This is known as cellular manufacturing and the system is called cellular manufacturing system and this is the most important application of group technology.

2.1.3 Cellular Manufacturing

Cellular manufacturing offers an opportunity to combine the efficiency of product flow layouts with the flexibility of functional layouts. Cellular manufacturing is a model of workplace design and includes the grouping of machines or processes on the basis of parts or part families' process. A group of parts which have similarities between them is known as a part family. The part families are distinguished based on the similar geometry or similar manufacturing process. The parts are not the same but they have so many similar features that they can be easily grouped separately (Groover, 2002).

Its main focus is to have different machines which help in manufacturing a part or a product or part families together. This is different from batch production where all the similar equipment is grouped together and if a part has to be machined, it has to go that place where that machine is located. This causes a lot of wastage in time.

The advantages of following this procedure are many. Due to the organized nature of the work cells, there is an increase in the production, proper utilization of the shop floor, reducing the waste, reducing the wastage of water, proper utilization of the floor space, shorter cycle times, effective production and lower production costs (Lei & Wu, 2005).

Various group technology methods have been classified into different types:

- Array based methods- In this method; the rows and columns of the zero one matrix are treated as words and rearranged to get a block diagram. One of the main examples is rank order clustering algorithm (ROC).
- Similarity coefficient based method- In this, the similarity is taken as the base for grouping the machines and parts using cluster analysis. The machines and parts are grouped separately and then assigned to each other.
- Cluster analysis- There are different types of analysis like hierarchical and nonhierarchical clustering. The hierarchical clustering considers each machine and eventually clusters them into a group.
- Graph theoretical methods- In this method, machines and parts are represented with the help of nodes and the processes which are necessary as arcs. So where there is no connection of arcs between nodes, they are taken into groups and formed as part families and machine cells.
- Mathematical programming methods- An integer programming formula called the p-median which maximizes the sum of similarity coefficients for the groups so that each part has a fixed cell.

There are a few mathematical matrices which are used for the clustering process. They are the incidence matrix and design structure matrix.

The part families are segregated by slowly grouping similar looking products to make the process easier and faster and this has continued ever since. It is a philosophy which helps identify similar looking parts and group them based on their manufacturing processes. The similarities on which they are separated can be based on a number of different things such as product design, processes or even administrative setups. The main purpose of cellular manufacturing is to increase the flexibility in an industry. This is done by improving the product design and process design. It is implemented by grouping the parts and the machines based on the processes that they have to follow.

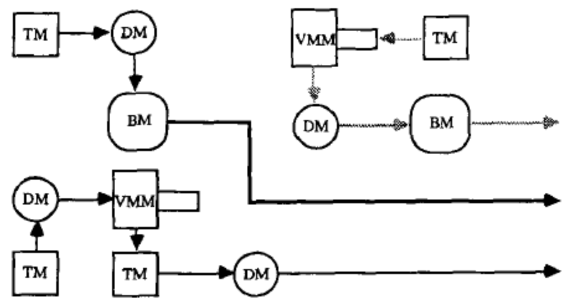

Figure 1: Layout for cellular manufacturing (Heragu, 1994)

The machines are grouped into cells so that each cell dedicated to the production of a certain part of the family (Heragu, 1994). Machines in each cell are different in their functions. Such an arrangement in which groups of machines are dedicated to specific parts of families allows for easier control of a CMS. Figure 1 shows an example of a CMS setup. The main objective in the design of a CMS is to create machine cells, identify part families, and allocate part families to machine cells so that the intercellular movement of parts of part families is minimized. Cellular manufacturing employs setup reduction and gives the workers the tools to be multiprocessors, operating multiple processes, and multifunctional, owning quality improvements, waste reduction, and simple machine maintenance. This allows workers to easily self-balance within the cell while reducing lead times, resulting in the ability for companies to manufacture high quality products at a low cost, on time, and in a flexible way. There are significant advantages which can be achieved as a result of reaction of a CMS (cellular manufacturing system).

It helped many companies in setting up time-saving, cost reduction in convey or technology, improving the quality and material flow.

It has a flexibility of producing high variety of products with low demand while maintaining the high productivity of large scale production. These are achieved by cell designers through modularity in process and product design. The process design of cellular manufacturing has the modularity which is to divide the entire production process into different segments, and then assign each segment to a work cell. If the process is to be changed, then the particular cell would be affected, but not the entire line of production.

A number of techniques exist in literature which allows the formation of groups in cellular manufacturing. They are classified as follows (Heragu, 1994):

- Rule of Thumb techniques: This is the basic of all the techniques. It does not have any strong base and the part families and machines are identified just by looking at them. These are not suitable for large scale manufacturing problems but are easy for small and quick ones.
- Classification and coding techniques: In this, the parts are grouped based on a number of characteristics like dimensions, material used, tolerance, composition of part, etc. A part is assigned a code comprising 10 to 30 digits which corresponds to an attribute of the part. Some parts have different type of relations between them like hierarchical, non-hierarchical and hybrid codes depending on the type of attribute that part is assigned.
- Production Flow Analysis: This is one of the most important and widely used techniques for cellular manufacturing. It groups the parts based only on the processes that they have to undergo. It takes into consideration only the information related to the process routings.

2.1.4 Production Flow Analysis

One of the most important techniques of group technology is the Production Flow Analysis. This is defined as the grouping of parts based only on the processes that they have to undergo. The parts are grouped into the same manufacturing cell based on the processes and the various equipment that they require. The grouping can be done by different approaches which are:

- Part family grouping – this means that the parts are formed into part families consisting of similar parts after which the machines are assigned to specific cells.
- Machine grouping – in this, the machines are grouped first according to their similarities and them the parts are assigned to cells.
- Machine-part grouping – here the parts as well as the machines are identified on their similarities simultaneously and then assigned to the cells.

The most important characteristic of PFA is the manufacturing method for the product. Its main concern is the route of the material flow. The PFA has four stages which are (Ribeiro dos Santos & Oliveira de Araújo, 2003):

- Factory Flow Analysis: This analysis is mainly concerned with the sequence of the paths that the product has to follow. It is important to look at which part families are going to which production units. Each part is given a unique Process Route Number (PRN) which tells the part the sequence of machines that it has to visit in order for its production process.
- Group Analysis: In the group analysis, a very important tool is used called the Incidence Matrix. This matrix represents the processes of the machines and parts and the groups that they belong to in a clear matrix format. The parts are divided into families and the machines into groups. The matrix is of the order of m x p where m is the number of machines and p is the number of parts. These machines and parts are grouped into cells based on the manufacturing processes that they have to undergo.
- Line Analysis: Here the analysis is made on all the cells to determine which line or which flow is best suitable for the machines and parts to follow.
- Tool Analysis: In this analysis, the incidence matrix gives information about the tools that are required for all the parts in a cell and helps to determine the selection process and sequence of the tools in order to save the setup times.

PFA has a lot of benefits. It helps to reduce costs and usage of unnecessary material and helps in utilizing a machine to its highest capacity. It has been very successful till date due to its detailed step by step procedure. The most important thing about Production Flow Analysis is that the grouping is done by a clustering process of the Incidence Matrix (IM).

2.1.5 Incidence Matrix (IM)

Incidence matrix is a matrix which helps in defining a relationship between the different clusters. The purpose of the incidence matrix is to get a relation between the machines and components so that they do not intersect. If the machine cells are clustered, then it will be easy for the part families to be assigned based on the maximum use of the machines. If the part families are grouped, then the machines can be clustered depending on which part family needs which machine the most. The various part families and machines are assigned before grouping them together. The assignment should be done such that there is maximum similarity in a group. The assignment is based on nonhierarchical clustering known as GRAFICS (Grouping Using Assignment Method for Initial Cluster Seeds) (Srinivasan G., 1991) so that in each cell, each part and machine have the maximum number 1's and minimum 0's which helps increase the density in a cluster.

The IM is usually defined by its m x p dimension. m represents the machines and p represents the parts. A perfect matrix solution for any clustering problem would be if there are 0's outside the diagonal box and only 1's inside the diagonal box. The binary numbers represent the relation between the parts and machines. If there is a relation, it is 1 otherwise 0. A matrix also shows the similarities between the parts in a part family in a given cell and the relations they have with the corresponding machine. Our main objective is to reduce the 0's outside diagonal and increase 1's in that place. This means that a particular part is assigned to a particular machine only. Sometimes, a machine can be assigned to more than one part and in that case the 1's may not necessarily be inside the diagonal. Figure 2 shows how a general matrix may look like which is Matrix A but a matrix after cell formation looks like Matrix B.

$$\begin{bmatrix} 1 & 0 & 0 & 1 & 0 \\ 1 & 1 & 1 & 1 & 0 \\ 0 & 1 & 0 & 1 & 0 \end{bmatrix} \qquad \begin{bmatrix} 1 & 1 & 1 & 0 & 0 \\ 1 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 \end{bmatrix}$$

Matrix A **Matrix B**

Figure 2: Matrix A: Before clustering; Matrix B: After clustering

One of the widely used techniques for clustering is using similarity coefficients (Sarker, 1996). The main factors which are considered for clustering in this way are the similarities between the parts and machines and grouping them into cells. The factors taken in consideration are given as (Sarker, 1996):

i. Number of parts processed on machines i and j
ii. Number of parts used by only machine i
iii. Number of parts used by only machine j
iv. Number of parts not used by either of the machines
v. The relation between the machines i and j is given as similarity index. Jacard's Similarity Coefficient is one of the most famous similarity indices and can be expressed as:

$$\text{Sij} = \sum_{\substack{k=1 \\ i \neq j}}^{n} \mathrm{d}\, k$$

Where $d_k=1$ if $a_{ik}=a_{jk}$ and $d_k=0$ the other way. This is one of the equations which is used to assign the different machines and components together to form a work cell.

2.2 Product Design Domain

The concept of a product life cycle is explained to understand how a final product is made. It shows how a product goes through different stages right from the initially acquiring the raw materials through manufacturing and assembling and finally to marketing it.

A product life cycle can also be defined on the basis of its sales. It goes through different stages given below.

- Introduction – Since it is the initial stage, a lot of money is invested in experiments and testing and introducing it into the market.
- Growth - This stage has full profits due to the advertising and more money is invested on the product for getting more returns.
- Maturity – Here, the product is fully established and has a good market share but it has reached its highest in sales.
- Decline – This is where new products start coming in and this product loses its hype and also the profits.

A lot of companies focus on mass production of products which is able to rake in the profits and at the same time also satisfies the needs of the customers. But now-a-days, due to the changes in the preferences of the customers and to keep up with the ever changing demands and specifications of the customers, manufacturing companies are trying to incorporate variety in the products that they offer. This is done by offering product variety by including the concept of product families (Roger Jiao et al., 2007). Product platforms can be defined as a set of components and parts from which a number of products can be developed efficiently and effectively (Simpson et al., 2005) . Product families have numerous advantages in creating variety in the products. Apart from having financial benefits such as achieving economies of scale and reducing risk, it can be used to enhance a product’s functionality and improve quality (Roger Jiao et al., 2007). It helps in keeping the original product platform intact while it allows the manufacturer to play with the design and functionality attributes keeping in mind the satisfaction of the customer. As it allows sharing of designs and components, it increases flexibility. It can be helpful in understanding the various components that make up a product and learn the interactions that are necessary in offering product variety.

The design of products can be achieved by developing the family of product in two ways. One is the top down approach and the other is the bottom up approach. The top down approach also known as the proactive platform approach (Simpson et al., 2005) is basically decomposing a system into several subsystems. These systems are then further broken down into simpler components which aid in understanding the functionality better. The bottom up approach also known as the reactive redesign approach (Simpson et al., 2005) is where the initial designs are developed from scratch and these are standardized into components. These components are then converted into product families for further customization and also help to increase the economies of scale.

Designing a product consists of five different domains which are customer, functional, physical, process and logistics.(Roger Jiao et al., 2007). The first domain consists of the customer needs (CN) and requirements. The functional domain converts these customer requirements into functional requirements (FR) by taking into consideration engineering specifications. This transition consists of problems related to developing a product family and it takes the help of an existing product family outline. In the physical domain, the solutions that have been obtained in the previous domain are graphed to design parameters (DP). The process domains convert the design parameters into process variables (PV). These process variables take care of the various manufacturing processes, the set of machines, tools and equipment. The final domain takes care of how to incorporate the product design into the supply chain network with the logistics variables (LV). It consists of various links in the supply chain such as suppliers, contractors, resource allocation, etc. and how to achieve coordination among them.

This process communicates how tedious it can be to manufacture a product and how many stages are present between the initial ideas of making a product to the final one. If any of the specifications changes, the entire setup has to undergo an evaluation. This demands investment of a lot of time, money and resources.

If there is a sudden increase in the variety, this kind of setup will not be able to keep up with the changing technological trends and cause a lot of loss to the companies. A solution to this can be tackled by taking into consideration the varieties in the products and taking advantage of the modularity that are present in a product.

The architecture of the products allows grouping the components of a part in such a way that the final process of manufacturing is done easy. This helps to accommodate the different designs and the modularity present between the components.

2.3 Variety Management in Design

With a wide range of designs being available for the customers in the products that they purchase, this has helped achieve a lot of variety as well in the products that are being offered. Manufacturing companies are able to produce numerous types of products in a single domain. The availability of product family design has led to the emergence of customization depending on the requirements of the individual. This is termed as product variety.

Product variety is of two types which are functional and technical variety (AlGeddawy & Elmaraghy, 2013). Functional variety can be defined in terms of the customers' point of view. It mainly focuses on satisfying the customers' needs with the quality and various functions offered by the product. It aims to include multiple specifications as requested by the customers. Technical variety is more concentrated on the process of manufacturing a certain product. It aims to reduce the technical difficulties faced while manufacturing in order to increase economies of scale and save time.

The purpose of having product variety is to provide flexibility for the customers in terms of the different types of choices that are offered. It helps to cater to a wider range of tastes. The demand for variety and customization of products is increasing rapidly and this helps to keep up with it. The variety a particular brand offers has a huge impact on the customers (Berger, Draganska, & Simonson, 2007). It directly influences them into going for a brand that has higher variety and range of choices to select from. It also sends a signal on the quality of the product and usually higher variety is associated with better quality. Manufacturing companies usually have to decide between focusing on low variety or having flexible manufacturing with high variety(Paul et al., 2011). Due to the rapid change in customer needs, the latter option is more likely to benefit the company.

But there may be questions raised regarding the motive of offering a high product variety. It may cause problems in the set up times for various manufacturing routings and processes, production costs will be higher and mixing of parts and components might be complex. But the benefits are far higher than the disadvantages. It is important to attract the customers' attention. It helps in gaining market share. With the ever changing trends in technology and improvements being made in every field, it is less expensive to adapt with the help of flexible manufacturing techniques.

To adapt to these changes easily, manufacturing companies make use of a concept known as product modularity. This concept is very important in creating product design and variety. A module is basically a collection of components or elements that share certain similar characteristics. Modularity is treating these various modules as independent units. Modules are separated into units based on the interactions among the components. Interactions within a modules are strong whereas within different modules are weak. Modularity helps to breakdown a system into simpler components and understand them better. Modularity is classified based on three important factors. They are functional modularity, technical modularity and physical modularity((Roger) Jiao et al., 2007). Functional modularity is characterized by the importance given to the functional requirements in a product family design. These mainly focus on the customer groups and their specifications. The technical modularity is based on the feasibility of the technical solutions and the equipment used. It focuses on whether the functional requirements are being satisfied by the design parameters or not in terms of manufacturing capabilities. The physical modularity mainly looks at how the physical features interact with one another after the part has been manufactured.

2.4 Modular Product Architecture

A product module consists of different product components that are strongly inter-connected with each other. (Simpson et al., 2005). The relationships between module components are very strong within that particular module while they are weakly connected to other components that belong to other modules. The purpose of a module is to easily create variety in products by combining, swapping and interchanging those modules. Relationships between product components are commonly represented in the form of a matrix called the Design Structure Matrix (DSM).

Product architecture (Eppinger & Browning, 2012) is defined as a process in which the functional elements and specifications of a product are arranged into different physical groups and the various interactions among them. There are different types of product architecture namely modular and integral. Modular architectures can be defined as product designs where there is more of individuality rather than coupling of components such that they act as individual units and integral architecture can be defined as components being more coupled to each other so that changes made in any one component affect the other components present.

While integral architecture is concentrated more towards improving the performance, modular architecture is concentrated more on increasing the flexibility of the product components. The concept of product architecture helps to handle various products simultaneously. Design Structure Matrix is a tool that helps in give a clear representation of component interactions in a system (Eppinger & Browning, 2012). The main application of DSM is in the field of engineering management but there are other areas where this has been used extensively like finance, health care, natural science and social science.

2.4.1 Design Structure Matrix

DSM is a tool that helps to give a clear representation of the interactions between the components in a system. A DSM is represented as a square matrix of the form NxN, in which system components are placed at the top row and the left column. The main applications of DSM are in the field of engineering management but there are other fields as well where it is being used such as finance, health care, natural science and social systems. There are a variety of systems and fields that can be shown on the DSM such as component based, people based, and activity based and parameter based.

The DSM helps in giving a clear and visual representation of all the complex interactions and communications among the various architectures. Figure 3 shows an example of a design structure matrix (T.R. Browning, 2001). It shows the different parameters that are taken into consideration. The diagonal across the matrix shows the elements that are present in the matrix. The interactions are shown as dots in the matrix. A dot which is present in any location other than the diagonal represents that one element is dependent on the other. The dots across a row shows what that particular element is contributing to and looking at the elements column wise tells what that particular element in that column is depending on (T.R. Browning, 2001). So, to put it simply, column wise gives the input and row wise shows the output.

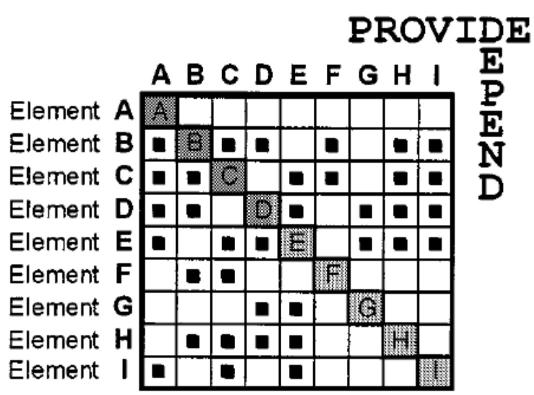

Figure 3: Example of the dependency in a DSM (T.R. Browning, 2001)

Over the years, other types of mappings have also evolved such as the numerical system and colors to shows the magnitude, strength and repetitiveness of an interaction between the components.

DSMs help a lot in building a clear picture of the various interactions between components, analyzing the connections and the complexities within the components. Even better understanding of the DSM can be achieved by using various tools to analyze them. One such tool is called clustering which is widely used in this field. It is a kind of partitioning carried out on the matrix to divide the components interactions into more clear groups. These groups can be created on basis of an objective relating to that particular DSM and most of these modules have more interactions within a module rather than with other modules. The main objective for any clustering process is to have more number of interactions within a particular cluster and less outside a cluster.

There are different types of DSM which are given below (Eppinger & Browning, 2012):

- Product Architecture DSM – This is related to how the components function and work together. It shows how the components are interacting with each other and the interactions with the outside environment also.
- Organization Architecture DSM – This shows how the people are related to each other in an organizational set and how they interact with each other from different departments and how they work together to complete their own individual tasks.
- Process Architecture DSM – This is defined as the interactions among different activities and the mapping between them. It shows the inputs and outputs that are necessary for an activity and how these work together.
- Multi-domain MDM – This is when more than one DSM is used to represent the interactions simultaneously. It is an extension of a single DSM.

To understand the relations between the components and modules, different types of dependencies and similarities were used such as:

- Component-component dependency – this is present between two components which are physically dependent on each other.
- Component-component similarity – this is the similarities between the physical components but it is not used in the present case study to allow any changes made in one component affect changes in another component.
- Component-process dependency – here those parts are grouped together in a module which even though do not have any dependencies but the processes they undergo are the same.
- Component-process similarity – here the components are grouped in such a way that they have the same life-cycle processes.

The last two are process-process dependency and process-process similarity. These are not taken into consideration as they do not affect the design of the products directly.

Any design structure matrix should represent modules which have a high degree of similarity and dependency within the modules and low degree of similarity and dependency between components of different modules. To measure the relative modularity, the following formula which is represented in Eq. 1 was used in the case study (Gershenson, Prasad, & Allamneni, 1999):

$$\text{Relative Modularity} = S_{in} / (S_{in} + S_{out}) + D_{in} / (D_{in} + D_{out}) \qquad (1)$$

Where,

S_{in} – Similarities between components of the same module

S_{out} – Similarities between components in a module to each component outside that module

D_{in} – Dependency between components of the same module

D_{out} – Dependency between components in a module to each component outside that module

Procedure for modeling a product architecture DSM (Eppinger & Browning, 2012):

- Breaking down the whole process into the basic activities. This includes any processes or stages that are required.
- Design a matrix which has all the tasks labelled on the rows and columns and grouped into the different processes.
- Identify the interactions between the elements and mark these on the DSM matrix.

The various rules that have to be followed while designing a DSM for a product are (Eppinger & Browning, 2012):

1. Boundaries- The limits of the extent of interactions must be well defined. It should try and include all possible relations between the components.
2. Interaction types- There are various types in the interactions between components. Some are clearly defined while others cannot be precise and are vague. These should be identified separately by marks and assigning colors.
3. Interaction strengths- The magnitude of certain interactions are more than others so these should be indicated clearly with the help of numbers. If some interactions are desirable and others are not, they can be represented with positive and negative numbers respectively.
4. Symmetry- Almost all DSM in product architecture are symmetric which means that the interactions between two components are mutual. But sometimes, it is asymmetric when one component affects another but not vice-versa.
5. Granularity- This means that it should be kept simple. We should be able to manage the size of our DSM by taking only a small number of components in the beginning and adding more if necessary.

Clustering is done to the DSM to get a better output of the interactions. The main objective of clustering is to get the best allocation of the components. The clustering analysis gives importance to various factors (S. D. ;Tyson. R. B. Eppinger, n.d.):

1. Number of clusters- The limits assigned to the clusters M.
2. Size- Another aim is to limit the size of the clusters. If the size of the cluster is allowed to increase, then there is a limit to the number of clusters.
3. Overlapping- Sometimes, if the interactions so demand, clusters may overlap each other for a better solution.
4. Integrating elements- Sometimes, some interactions do not belong inside a cluster. This is because these elements are highly important and interact with many components.
5. Manual Clustering- Sometimes, clustering is done manually rather than using software by moving the rows and columns.
6. Multiple clustering solutions- As we know that modularization means it can have more than one solution; we should consider all of them before selecting one.

An example for clustering based on the transfer type of interactions is shown in Figure 4 and it is seen that 3 clusters have been formed on this basis. The transfer type of interactions are interior air, refrigerant, front-end air. From the resulted DSM, it can be seen that there are different clusters with different types of interactions and it all depends on how each component is connected to the others.

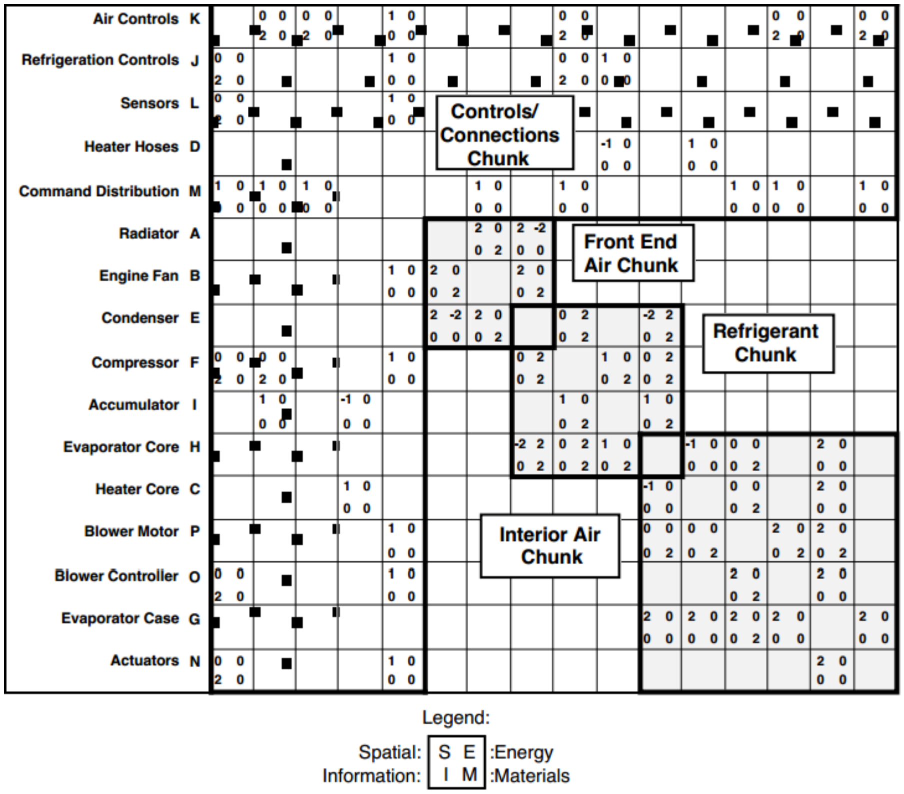

Figure 4: Clustered DSM for the Climate Control System Example (S. D. ;Tyson. R. B. Eppinger, n.d.)

2.5 Research Gap and Opportunities

To manufacture a product, there are many things that are taken into consideration. The raw materials required, the different manufacturing processes that have to applied, the time taken to produce them and also the cost for the entire process. In this age, customers are mainly concerned with the price that they have to pay and also how much time they have to wait before they can lay hands on their customized product.

There are many techniques and algorithms like the ones presented previously on how to manufacture each complete product and also each part individually and separately using methods such as clustering algorithms and procedures like cellular manufacturing and production flow analysis. But to make a complete product, it requires a combination of both the machine cells required by that particular product as well as the components of a part. There is a need to combine these two processes and that too, efficiently and taking as much less time as possible.

The next chapter proposes to experiment with a combined formula that targets both the manufacturing side of the products as well as the design process for making that product and eventually aim to make the overall manufacturing process as efficient as possible.

It shows in detail how the machines cells are clustered and how the modules of a product are clustered simultaneously and efficiently. The model uses a series of matrices and vectors that are used to combine with the present DSM and IM. This results in a new DSM and IM combined into a single matrix which shows the interaction between the modules and the cells at the same time. Thus, it is treated as working with multi domains in the manufacturing and design world and creating an algorithm which helps to combine the best of manufacturing efficiency with time.

CHAPTER 3

3.1 The Multi-Domain Manufacturing and Design Model

The main objective of the proposed Multi-Domain Manufacturing and Design (MD-MD) model is to establish one-to-one association between product modules and machine cells. Figure 5 clearly represents the matrices where the modules of a part interact with each other and the cells of machines interact with each other. It shows how the respective vectors are applied to each of the matrices and how they are clustered.

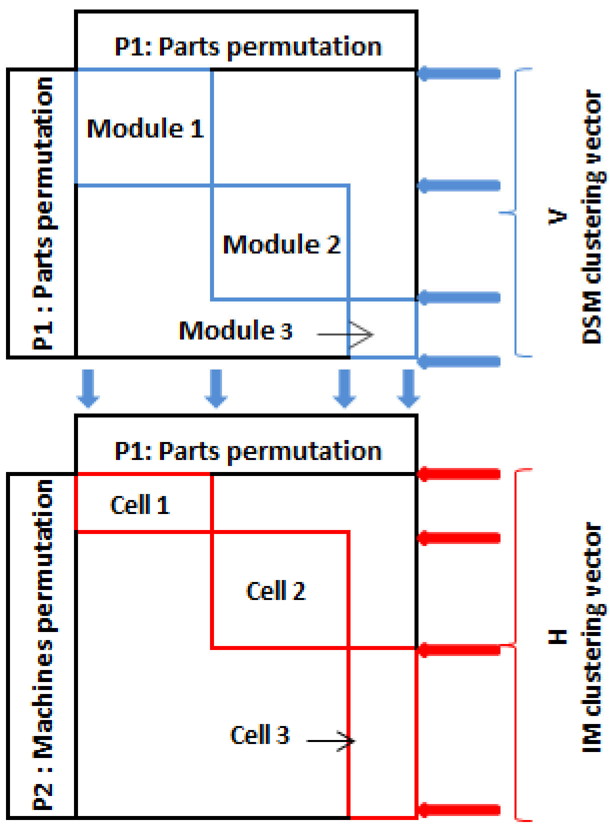

Figure 5: Clustering of DSM and IM

This model is represented with the help of IDEF0. It is an acronym for ICAM Definition for Function Modeling where ICAM stands for Integrated Computer Aided Machining. This is a methodology which consists of the various activities described structurally for easy analysis of the model. This was first developed by the US Air Force to give a detailed explanation of the processes in manufacturing facility with clear graphical representations (GAY, 1993).

Figure 6 shows a simple example of an IDEF0. There is a simple syntax related to the figure. A box represents the function. The function can be an activity or a phrase which describes what action it performs. There are typically four arrows around a function. An input arrow that goes in from the left side of the box shows what inputs are given to the function. An output arrow that comes out from the right side of the box which gives the output achieved. Controls or constraints for the function go in from the top and the mechanism that is being implemented goes in from the bottom of the box. The IDEF0 helps in giving a very detailed step by step understanding of methods and tasks. The model can be shown in as detail as possible. It helps in portraying a logical representation of mathematical models, functions or activities.

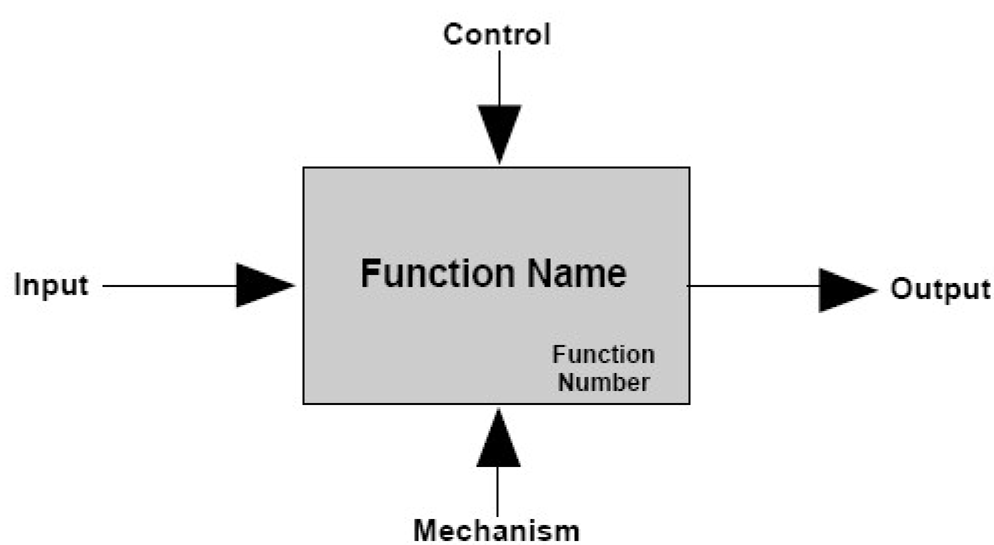

Figure 6: Representation of IDEF0 (Defense Acquisition University Press, 2001)

In the present model, the whole mathematical model or an activity can be divided into sub activities.

The two main activities are Shuffling and Clustering represented as A1 and A2 as shown in Figure 7.

The final output from the activity 2 is the matrices with the respective clusters. The matrices are then evaluated for the optimality with an objective function which is shown in Equation 1. The final outcome will be the best clustered DSM and IM.

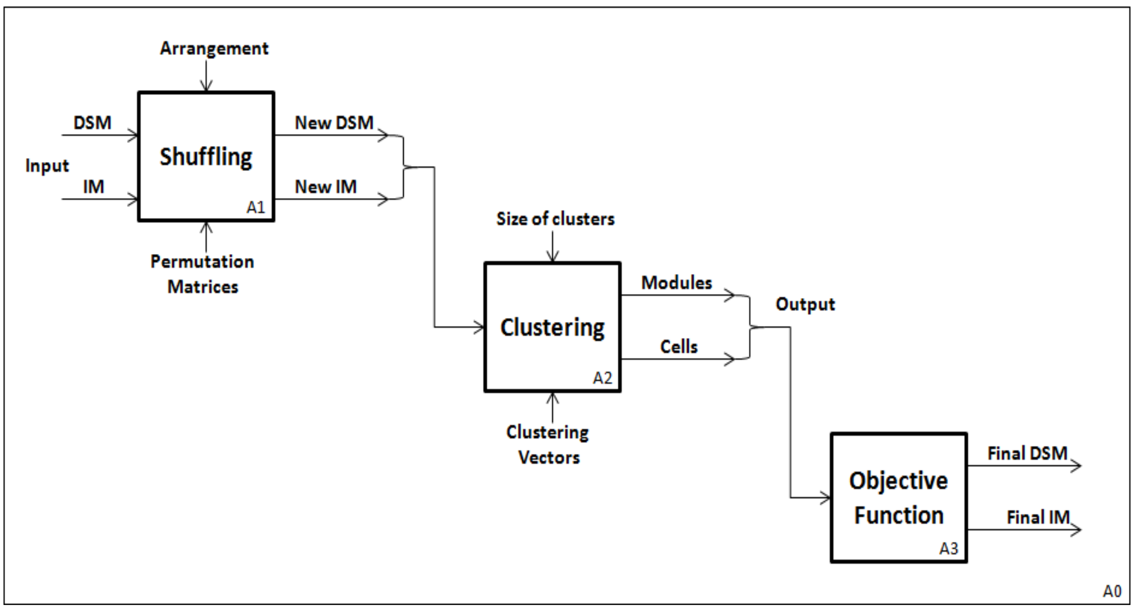

Figure 7: IDEF0 for a life cycle function

Shuffling consists of two inputs which are the two matrices, DSM and IM as shown in Figure 8. These matrices undergo shuffling with the help of permutation matrices. The permutation matrices form the mechanism which aids the shuffling process. The input matrices are subject to constraints in the form of the arrangement of the indices. While they are being shuffled using a mathematical formula, the arrangement of the parts in the DSM and the machines and parts in the IM undergo a lot of swapping and this should be recorded to understand later how the machines and parts are interacting with each other in the IM and how the components of parts are interacting with each other in the DSM.

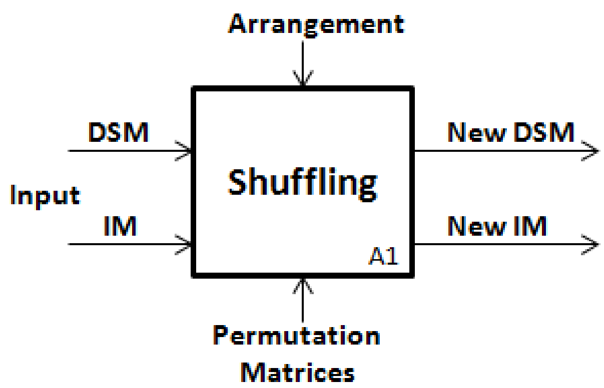

Figure 8: Activity 1

Once the shuffling process is performed, a new DSM and IM are generated which will be the input for the second activity called Clustering as shown in Figure 9. Clustering is a process where the part components are arranged into modules and the parts and machines are arranged into cells. The mechanism for this clustering technique is achieved with the use of clustering vectors H and V. The vector V is used for clustering the DSM whereas the H as well as the V vectors is used for the clustering of the IM. However, there is another constraint in this activity in the form of the number of clusters achieved. The total number of clusters should be equal in both the DSM and the IM so the constraint is on the clustering vectors where we control the number of 1's in the clustering vectors for the optimal output. The output achieved is the final DSM and IM with the modules and cells.

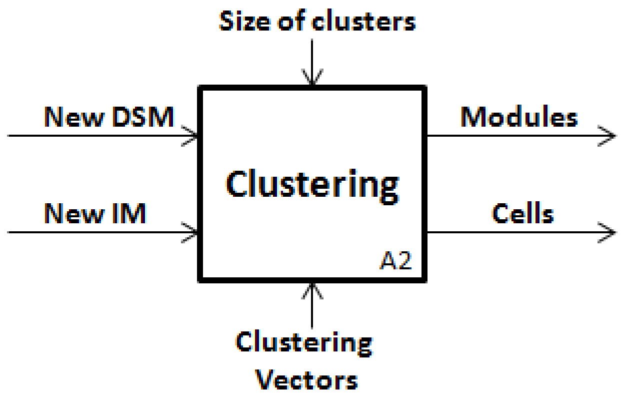

Figure 9: Activity 2

The final activity as shown in Figure 10 is the calculation of the objective function. This is shown in equation 2 where the total number of 0's inside the modules and cells and the total number of 1's outside the modules and cells are counted. This number has to be minimized so it is an optimization activity. The input for this activity will be the modules and cells formed in the activity 2. The output will be the final DSM and final IM with the calculated objective function value.

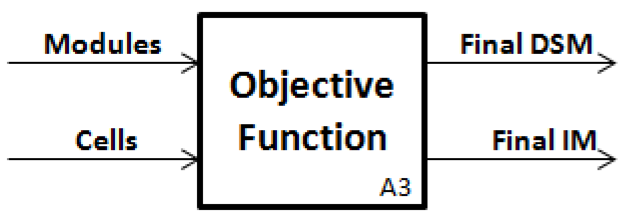

Figure 10: Activity 3

The objective function for this model is given as:

$$Minimize\ F = w1\times(F1\{Modules\} + F0\{Modules\}) + w2\times(F1\{Cells\} + F0\{Cells\} \qquad (2)$$

The objective function of the model is to minimize the number of 1's outside the modules and cells and maximize the number of 0's outside the cells and modules simultaneously. The objective function is presented in equation

The model uses a set of permutation matrices and clustering vectors to rearrange products and machines in the given DSM and IM. Those permutation matrices and vectors govern the mathematical constraints of the model, which are expressed in the equations from (3) to (7).

The model uses a set of permutation matrices and clustering vectors to rearrange products and machines in the given DSM and IM. Those permutation matrices and vectors govern the mathematical constraints of the model, which are expressed in the equations from 3 to 7.

The variables used are explained below:

F is the summation of clustering results from both DSM and IM.

F_1 is the number of the '1' elements outside clusters (modules or cells).

F_0 is the number of '0' elements inside clusters (modules or cells).

w_1 is the arbitrary weight of the design domain.

w_2 is the arbitrary weight of the system domain.

P_1: Permutation matrix to arrange parts in the original DSM and IM into DSM_{new} and IM_{new}. P_1 is a binary matrix.

P_2: Permutation matrix to arrange machines in the original IM into IM_{new}. P_2 is a binary matrix.

V: Clustering vector to modularize DSM_{new} and IM_{new}. V is a binary vector.

H: Clustering vector to partition IM_{new}. H is a binary vector.

N_M: Number of produced product modules.

N_C: Number of produced machine cells.

Subject to:

$$\mathrm{DSM_{new}} = \mathrm{P_1} \times \mathrm{DSM} \times \mathrm{P_1}^{\mathrm{T}} \tag{3}$$

$$\mathrm{IM_{new}} = \mathrm{P_2} \times \mathrm{IM} \times \mathrm{P_1}^{\mathrm{T}} \tag{4}$$

$$\mathrm{DSMf} = \mathrm{V} \times \mathrm{DSM_{new}} \times \mathrm{V}^{\mathrm{T}} \tag{5}$$

$$\mathbf{IMf} = \mathbf{H} \times \mathbf{IM_{new}} \times \mathbf{V}^{\mathbf{T}} \tag{6}$$

Where,

$\mathbf{N_M} = \mathbf{N_C}$,

$\mathrm{P_{1i}}, \mathrm{P_{2i}}, \mathrm{V_i}, \mathrm{H_i} = \{1,0\} \; \forall \; \mathrm{i}$

A permutation matrix is a square binary matrix. It has only one 1 in each row and column with the rest all being 0. It is similar to an identity matrix but with the rows interchanged from their original positions. A permutation matrix helps in the interchanging of rows and columns. It depends on the position of the permutation matrix. If a permutation matrix is on the left side of another matrix, then the rows get interchanged and if it is on the right side of the matrix, then the columns get interchanged("Permutation Matrices," n.d.). This is shown in Figures 11 and 12 respectively.

$$\begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} x_2 \\ x_3 \\ x_1 \end{bmatrix}, \qquad \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} a & a & a \\ b & b & b \\ c & c & c \end{bmatrix} = \begin{bmatrix} b & b & b \\ c & c & c \\ a & a & a \end{bmatrix}.$$

Figure 11: Left multiplication of a permutation matrix

$$\begin{bmatrix} a & b & c \\ a & b & c \\ a & b & c \end{bmatrix} \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \end{bmatrix} = \begin{bmatrix} c & a & b \\ c & a & b \\ c & a & b \end{bmatrix}, \qquad \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} a & b & c \\ d & e & f \\ g & h & i \end{bmatrix} \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \end{bmatrix} = \begin{bmatrix} f & d & e \\ i & g & h \\ c & a & b \end{bmatrix}$$

Figure 12: Right multiplication of a permutation matrix

Figures 13 and 14 demonstrate how the permutation matrices are used to re-arrange given DSM and IM and generate a new DSM and IM.

$$\underset{P}{\begin{bmatrix} 0&0&0&1&0\\ 0&0&1&0&0\\ 1&0&0&0&0\\ 0&0&0&0&1\\ 0&1&0&0&0 \end{bmatrix}} \times \underset{\text{Original Matrix}}{\begin{array}{c|ccccc} & 1&2&3&4&5\\ \hline 1&1&0&1&1&1\\ 2&0&0&0&1&0\\ 3&1&1&1&0&0\\ 4&0&1&1&1&0\\ 5&1&0&0&1&0 \end{array}} \times \underset{P^T}{\begin{bmatrix} 0&0&1&0&0\\ 0&0&0&0&1\\ 0&1&0&0&0\\ 1&0&0&0&0\\ 0&0&0&1&0 \end{bmatrix}} = \underset{\text{Final Matrix}}{\begin{array}{c|ccccc} & 4&3&1&5&2\\ \hline 4&1&1&0&0&1\\ 3&0&1&1&0&1\\ 1&1&1&1&1&0\\ 5&1&0&1&0&0\\ 2&1&0&0&0&0 \end{array}}$$

Figure 13: Re-arrangement of DSM using permutation matrices

$$\underset{P_2}{\begin{bmatrix} 0&0&1&0&0&0\\ 0&1&0&0&0&0\\ 1&0&0&0&0&0\\ 0&0&0&0&1&0\\ 0&0&0&1&0&0\\ 0&0&0&0&1&0 \end{bmatrix}} \times \underset{\text{Original Matrix}}{\begin{array}{c|ccccc} & 1&2&3&4&5\\ \hline 1&0&1&0&0&1\\ 2&1&0&1&1&0\\ 3&0&1&0&0&1\\ 4&1&0&1&1&0\\ 5&1&1&1&0&1\\ 6&1&0&1&0&1 \end{array}} \times \underset{P_1^T}{\begin{bmatrix} 0&0&1&0&0\\ 0&0&0&0&1\\ 0&1&0&0&0\\ 1&0&0&0&0\\ 0&0&0&1&0 \end{bmatrix}} = \underset{\text{Final Matrix}}{\begin{array}{c|ccccc} & 4&3&1&5&2\\ \hline 3&0&0&0&1&1\\ 2&1&1&1&0&0\\ 1&0&0&0&1&1\\ 6&0&1&1&1&0\\ 4&1&1&1&0&0\\ 5&0&1&1&1&1 \end{array}}$$

Figure 14: Re-arrangement of IM using permutation matrices

Clustering is the process of organizing and dividing a group of items in such a way that items in a particular groups or clusters have similarities among them compared to object belonging to other groups (Feng, 2012). The vectors try to arrange and distribute the clusters using various algorithms (Fernández, V. et al.,2000). An example of how a clustering vector looks like is shown in Figure 15.

1
0
0
1
1

Figure 15: Example of a clustering vector

The permutation vectors P1 and P2 which are shown in Figures 16 and 17 are used to rearrange the parts and machines of an incidence matrix and also the components of parts in a design structure matrix.

0	0	0	1	0
0	0	1	0	0
1	0	0	0	0
0	0	0	0	1
0	1	0	0	0

Figure 16: Permutation vector (P1) for DSM

0	0	1	0	0	0
0	1	0	0	0	0
1	0	0	0	0	0
0	0	0	0	1	0
0	0	0	1	0	0
0	0	0	0	1	0

Figure 17: Permutation vector (P2) for DSM and IM

After multiplying these vectors with the DSM and IM vectors with the formula

$$DSMf = P1 * DSM * P1'$$

$$IMf = P2 * IM * P1'$$

Where P1’ stands for the transpose of the matrix P1

We get the new matrices as shown in Figures 18 and 19.

	4	3	1	5	2
4	1	1	0	0	1
3	0	1	1	0	1
1	1	1	1	1	0
5	1	0	1	0	0
2	1	0	0	0	0

Figure 18: DSMnew

	4	3	1	5	2
3	0	0	0	1	1
2	1	1	1	0	0
1	0	0	0	1	1
6	0	1	1	1	0
4	1	1	1	0	0
5	0	1	1	1	1

Figure 19: IMnew

Now horizontal and vertical vectors are applied to these matrices. We take a number of vectors and multiply the DSM and IM with them to get a connection between the two matrices.

V and H are vectors which are applied to the DSM and IM to get the modules and cells respectively. The use of the permutation vectors helps give a connection to both the matrices and these variables are used in the optimization process to get the solution.

Figures 20 and 21 demonstrate how clustering vectors are used to cluster a given DSM into modules of components and a given IM into cells of machines, and keep them associated.

The new DSM is multiplied with only the horizontal vector H whereas the new IM which has the parts and the machines is multiplied with both the horizontal vector H and the vertical vector V.

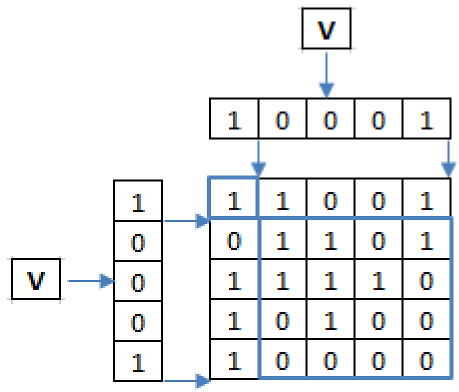

Figure 20: Applying vector V to DSMnew

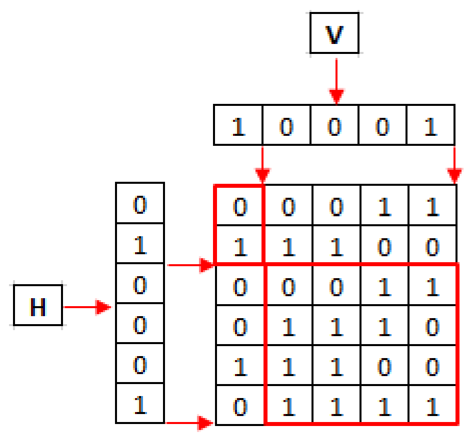

Figure 21: Applying vectors H and V to IMnew

3.2 Genetic Algorithm

Genetic Algorithms are an effective search and optimization techniques. It comprises a number of populations where in each generation, the better population is kept while the others are discarded (Matouš, Lepš, Zeman, & Šejnoha, 2000). This technique is similar to the natural biological process where the off springs of humans are born through a natural process of selection where in each generation; a better chromosome is selected for the best outcome. The GA uses a chromosome which consists of various inputs necessary for the mathematical function. This chromosome is then evaluated based on a fitness function. A fitness function is a primary objective which decides whether the chromosome is capable of giving a feasible solution or not. The feasibility of the chromosome is analyzed by performing two main operations: mutation and crossover. Mutation is a process where a cell or a particular number of cells of a chromosome are replaced with a different value suitable for the optimization model. A crossover occurs when a portion of two different chromosomes are swapped and replaced with each other. Figure 22 is a representation of crossover and mutation.

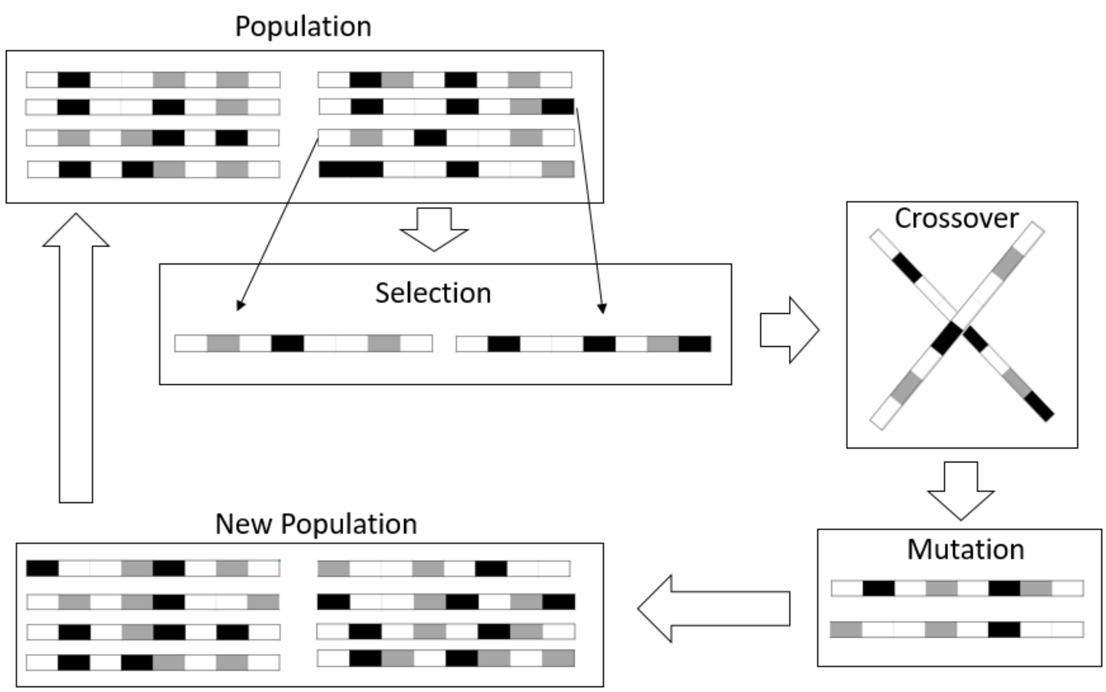

Figure 22: A common genetic process (Lin, Lee, & Hong, 2003)

In the present mathematical model, there are four different vectors and matrices that form a chromosome. They are the horizontal vector H, vertical vector V and permutation matrices P1 and P2. Since the mathematical model requires optimization, this is the best way to obtain good results. Initially, a population is created which has a particular number of chromosomes. A part of the population is mutated, crossover is done on another small part of it and the rest of the population is retrieved from the initial population. Every time a new population is generated, the best ones are kept for the next iterations while the others are discarded. In this way, we apply each chromosome to the objective function and test for the results.

The present model poses a few challenges. There are a number of algorithms that can cluster the DSM and IM individually. Since the objective is to cluster them simultaneously, a lot of factors pose as constraints.

3.3 Pseudo Code for the Genetic Algorithm

The following steps are followed to obtain the result using Genetic Algorithm.

1. Declare the variables.
2. Initialize the matrices DSM, IM, permutation matrices P_1 and P_2 ,and vectors H and V as well as other variables.
3. Start a loop for x number of iterations.
4. Multiply the matrices DSM and IM with the permutation matrices P_1 and P_2 to shuffle the arrangement of the initial matrices DSM and IM.
5. Store the final DSM, IM, P_1 and P_2.
6. Stop loop.
7. Start a loop for n number of iterations.
8. Randomize the vectors H and V by shuffling the location of 1's inside the vectors.
9. Store the final vectors H and V.
10. Stop loop.
11. Group the final matrices DSM and IM into modules and cells with the help of the clustering vectors H and V.
12. Apply the mathematical function to the final DSM and IM to get the best solution.

CHAPTER 4

CASE STUDIES

In this chapter, a number of different case studies have been taken from literature for reference. These case studies are analyzed and compared with the solutions obtained in literature and also the solutions obtained from the code that has been developed. A comparison is made with the individual DSMs and IMs and also with the combined DSM and IM examples. In the examples where only the DSM and IM have been taken individually and compared, the results are close to the ones obtained in literature and in some cases, even better. But we can see that in the example where both of them have been taken together, solutions are not as good as what we might expect. The reasons and analysis is presented at the end of this chapter.

Test for DSM Example No. 1

This case study has been taken from(Tyson R. Browning, n.d.). This DSM shows the various parts of a climate cooling system and how the materials are interacting with each other. The results for this example are shown in Figure 23. Figure 24 shows the graph with the results at each iteration and how they improve eventually.

The function value (F) calculated for both the solutions are:

Minimize F (best solution in lit) = 12

Minimize F (output of the model solution) = 10

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
2	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0
3	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1
4	0	1	0	1	1	0	1	0	0	0	0	0	0	0	0
5	0	0	0	1	1	0	1	1	0	0	0	0	0	0	0
6	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1
7	0	0	0	1	1	0	1	1	0	0	0	0	0	0	1
8	0	0	0	0	1	0	1	1	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
14	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1
15	0	0	1	0	0	1	1	0	0	0	0	0	0	1	1

(a)

	9	10	11	12	13	1	2	4	5	8	7	3	15	14	6
9	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
11	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0
2	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0
4	0	0	0	0	0	0	1	1	1	0	1	0	0	0	0
5	0	0	0	0	0	0	0	1	1	1	1	0	0	0	0
8	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0
7	0	0	0	0	0	0	0	1	1	1	1	0	1	0	0
3	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0
15	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1
14	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0
6	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1

(b)

	9	8	7	5	4	13	3	2	1	10	6	15	14	11	12
9	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0
7	0	1	1	1	1	0	0	0	0	0	0	1	0	0	0
5	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0
4	0	0	1	1	1	0	0	1	0	0	0	0	0	0	0
13	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0
2	0	0	0	0	1	0	0	1	1	0	0	0	0	0	0
1	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0
15	0	0	1	0	0	0	1	0	0	0	1	1	1	0	0
14	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0
11	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1

(c)

Figure 23: (a) Problem given in literature (b) Best solution in literature (c) Output of the model solution along with the arrangement of parts(Tyson R. Browning, n.d.)

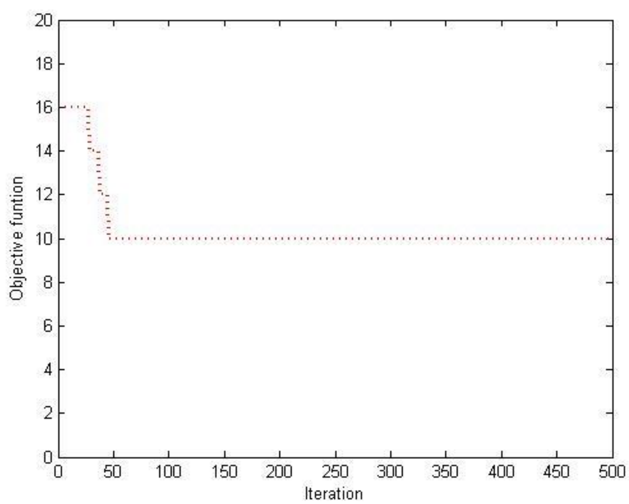

Figure 24: Graph of convergence

Test for DSM Example No. 2

This example has been taken from(AlGeddawy & Elmaraghy, 2013). It shows a matrix of states and characters before being clustered. The output for this example is shown in Figure 25 and the results at each iteration of the code are shown in the graph in Figure 26. The function value calculated for both the solutions are

Minimize F (best solution in lit) = 4

Minimize F (output of the model solution) = 4

	1	2	3	4	5	6
1	1	1	0	0	0	1
2	1	1	0	0	0	0
3	0	0	1	1	1	0
4	0	0	1	1	1	1
5	0	0	1	1	1	1
6	1	0	0	1	1	1

(a)

	3	4	5	6	1	2
3	1	1	1	0	0	0
4	1	1	1	1	0	0
5	1	1	1	1	0	0
6	0	1	1	1	1	0
1	0	0	0	1	1	1
2	0	0	0	0	1	1

(b)

	1	2	5	6	4	3
1	1	1	0	1	0	0
2	1	1	0	0	0	0
5	0	0	1	1	1	1
6	1	0	1	1	1	0
4	0	0	1	1	1	1
3	0	0	1	0	1	1

(c)

Figure 25: (a) Problem given in literature (b) Best solution in literature (c) Output of the model solution along with the arrangement of parts(AlGeddawy & Elmaraghy, 2013)

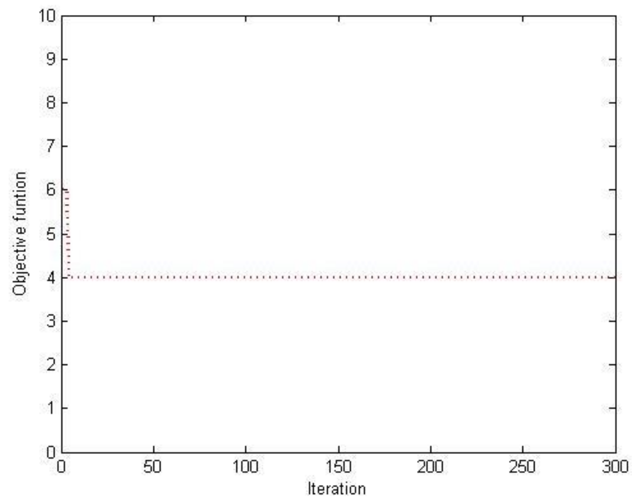

Figure 26: Graph of convergence

Test for DSM Example No. 3

This example has been taken from(AlGeddawy & Elmaraghy, 2013). Figure 29 shows the initial structure of the DSM. This shows the various metal parts of an automobile body that has to be initially welded and then taken for further painting. The parts are initially arranged in alphabetical order. Figures 27 and 28 show the initial look of the matrix and the final solution obtained in literature whereas Figure 29 shows the output of the model obtained through the code. The convergence graph of various solutions is shown in figure 30.

The function value calculated for both the solutions are

Minimize F (best solution in lit) = 158

Minimize F (output of the model solution) = 186

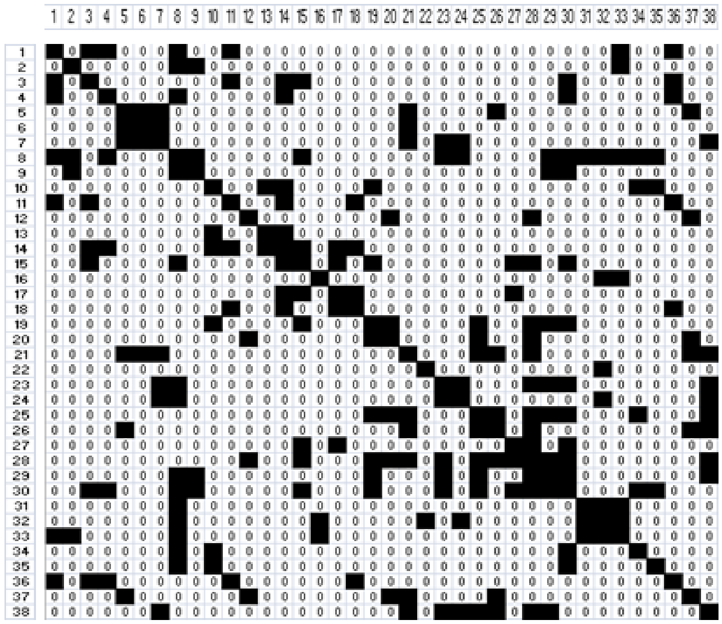

Figure 27: Problem given in literature(AlGeddawy & Elmaraghy, 2013)

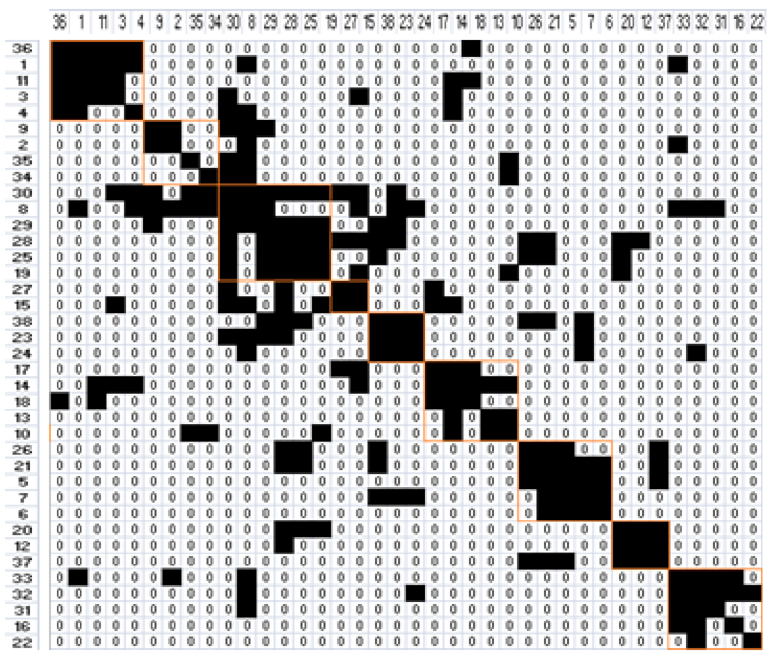

Figure 28: Best solution in literature

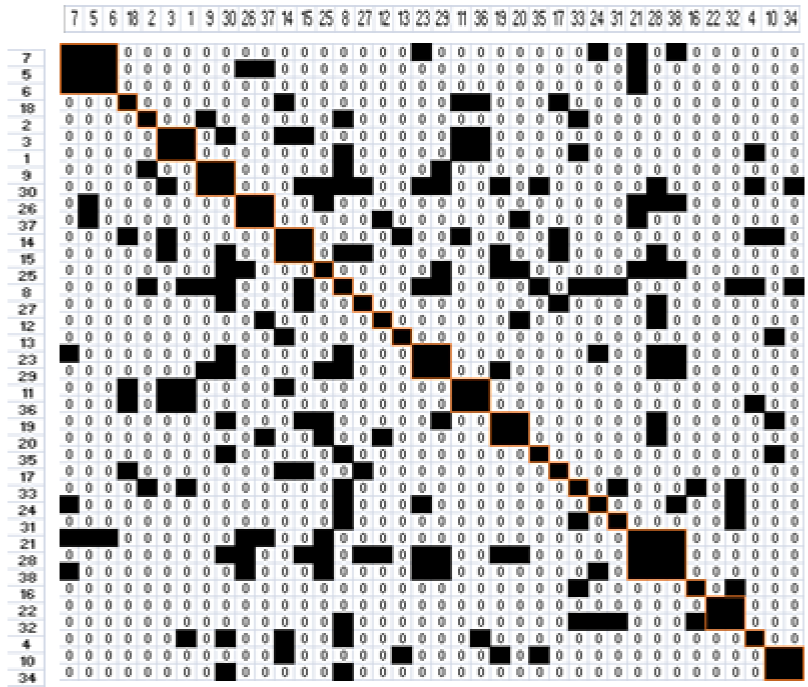

Figure 29: Output of the model solution along with the arrangement of parts

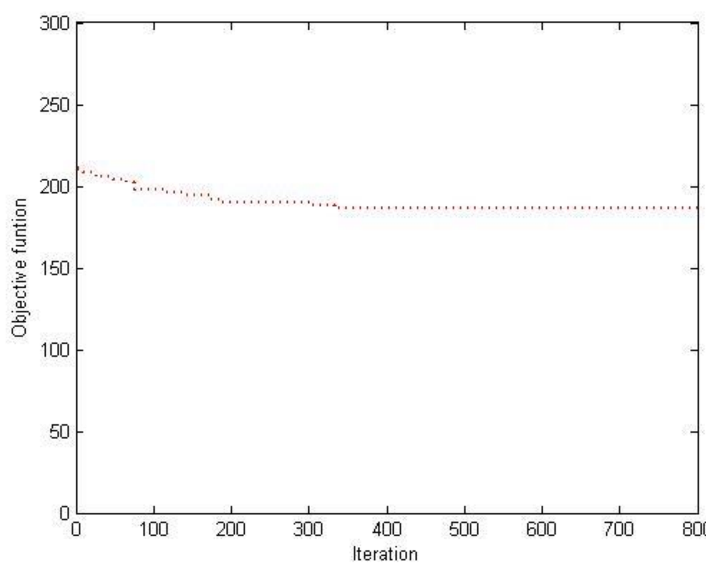

Figure 30: Graph of convergence

Test for DSM Example No. 4

This final DSM is the main example for this thesis. Figure 31 shows the initial and final DSMs. Figure 32 shows the convergence graph of the different solutions.

The function value calculated for both the solutions are

Minimize F (output of the model solution) = 34

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1	1	1	1	0	0	0	1	1	0	1	0	1	0	0	1	1	1	1	0
2	1	1	0	1	1	1	0	0	0	0	1	0	1	0	0	0	0	0	1
3	1	0	1	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0
4	0	1	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
5	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1
6	0	1	0	0	0	1	0	0	0	0	1	0	1	0	0	0	0	0	0
7	1	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	1	0
8	1	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0
9	0	0	1	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0
10	1	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0
11	0	1	0	0	0	1	0	0	0	0	1	0	1	0	0	0	0	0	0
12	1	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0
13	0	1	0	1	0	1	0	0	0	0	1	0	1	0	0	0	0	0	0
14	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
15	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
16	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
17	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
18	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0
19	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1

(a)

	2	6	13	18	12	7	1	9	8	10	11	17	5	15	4	16	19	3	14
2	1	1	1	0	0	0	1	0	0	0	1	0	1	0	1	0	1	0	0
6	1	1	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
13	1	1	1	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0
18	0	0	0	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0
1	1	0	0	1	1	1	1	0	1	1	0	1	0	1	0	1	0	1	0
9	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	1	0
8	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0
11	1	1	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0
5	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0
15	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0
4	1	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
16	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0
19	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0
3	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	1	1
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1

(b)

Figure 31: (a) Problem given in literature (b) Output of model solution along with the arrangement of parts (Tyson R. Browning, n.d.)

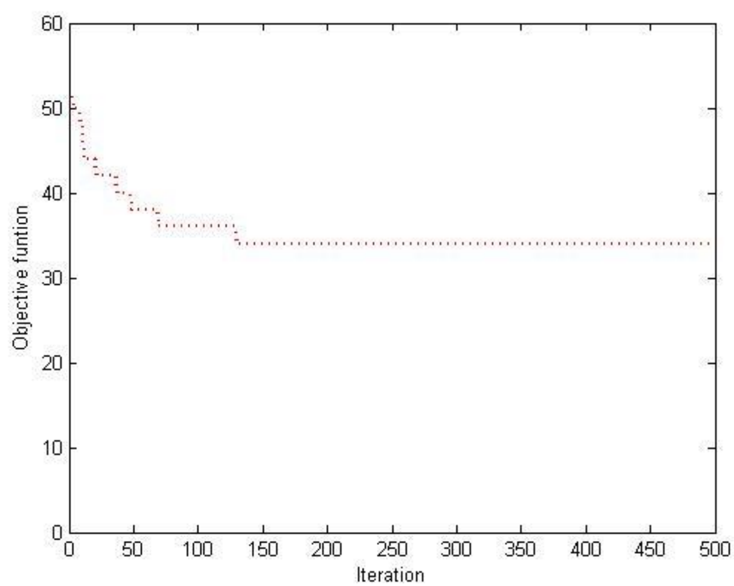

Figure 32: Graph of convergence

Test for IM Example No. 1

This case study is on IM. Figure 33 shows the different matrices and solutions whereas Figure 34 shows the graph at each iteration.

The function value calculated for both the solutions are

Minimize F (best solution in literature) = 5

Minimize F (output of the model solution) = 6

	1	2	3	4	5	6	7	8
M1	1	0	1	0	0	1	0	1
M2	1	0	0	0	0	1	0	0
M3	0	1	0	0	0	0	0	1
M4	1	0	1	0	0	1	0	0
M5	0	0	0	1	0	0	1	0
M6	0	1	0	0	1	0	0	1
M7	0	0	0	0	1	0	0	1
M8	1	0	1	0	0	1	0	0
M9	0	0	0	1	0	0	1	0
M10	0	1	0	0	0	0	1	0

(a)

	1	6	3	8	5	2	7	4
M2	1	1	0	0	0	0	0	0
M4	1	1	1	0	0	0	0	0
M8	1	1	1	0	0	0	0	0
M1	1	1	1	1	0	0	0	0
M7	0	0	0	1	1	0	0	0
M6	0	0	0	1	1	1	0	0
M3	0	0	0	1	1	1	0	0
M10	0	0	0	0	0	1	1	0
M5	0	0	0	0	0	0	1	1
M9	0	0	0	0	0	0	1	1

(b)

	3	6	1	5	8	2	7	4
M4	1	1	1	0	0	0	0	0
M1	1	1	1	0	1	0	0	0
M8	1	1	1	0	0	0	0	0
M2	0	1	1	0	0	0	0	0
M7	0	0	0	1	1	0	0	0
M6	0	0	0	1	1	1	0	0
M10	0	0	0	0	0	1	1	0
M3	0	0	0	0	1	1	0	0
M9	0	0	0	0	0	0	1	1
M5	0	0	0	0	0	0	1	1

(c)

Figure 33: (a) Problem given in literature (b) Best solution in literature (c) Output of the model solution along with the arrangement of parts(Daita, Irani, & Kotamraju, 1999)

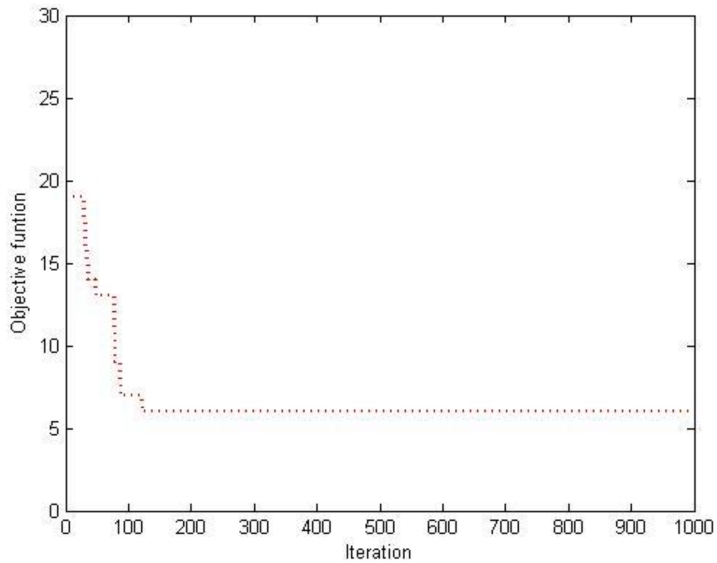

Figure 34: Graph of convergence

Test for IM Example No. 2

This is a simple example of an IM which shows different parts and machines. Figure 35 shows the initial and final matrices obtained from literature and from the code and Figure 36 shows a graph which depicts how the results have converged with each iteration.

The function value calculated for both the solutions are

Minimize F (best solution in literature) = 0

Minimize F (output of the model solution) = 0

	1	2	3	4	5
M1	1	0	0	1	0
M2	0	1	1	0	1
M3	1	0	0	1	0
M4	0	1	1	0	1
M5	1	0	0	1	0

(a)

	2	3	5	1	4
M2	1	1	1	0	0
M4	1	1	1	0	0
M1	0	0	0	1	1
N3	0	0	0	1	1
M5	0	0	0	1	1

(b)

	2	5	3	4	1
M4	1	1	1	0	0
M2	1	1	1	0	0
M3	0	0	0	1	1
M5	0	0	0	1	1
M1	0	0	0	1	1

(c)

Figure 35: (a) Problem given in literature (b) Best solution in literature (c) Output of the model solution along with the arrangement of parts and machines(Wu, Tai-Hsi; Chung, Shu-Hsing; Chang, 2009)

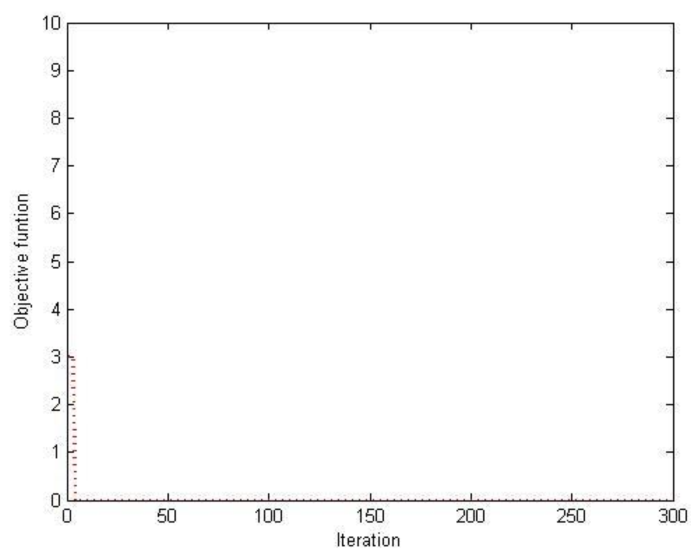

Figure 36: Graph of convergence

Test for IM Example No. 3

This is another classic example which shows the cell formation in an IM. Figure 37 shows the output for this IM and figure 38 shows the convergence graph of the different solutions.

The function value calculated for both the solutions are

Minimize F (best solution in literature) = 13

Minimize F (output of the model solution) = 13

	1	2	3	4	5	6	7	8	9	10	11
M1	0	0	1	0	1	0	1	0	0	0	0
M2	1	1	0	1	0	1	0	1	1	0	1
M3	0	0	0	0	1	0	1	0	0	0	1
M4	0	1	1	1	1	1	0	1	1	1	0
M5	1	1	0	1	0	0	0	1	0	1	1
M6	1	1	0	0	0	0	0	1	1	0	0

(a)

	1	2	4	6	8	9	10	11	3	5	7
M2	1	1	1	1	1	1	0	1	0	0	0
M4	0	1	1	1	1	1	1	0	1	1	0
M5	1	1	1	0	1	0	1	1	0	0	0
M6	1	1	0	0	1	1	0	0	0	0	0
M1	0	0	0	0	0	0	0	0	1	1	1
M3	0	0	0	0	0	0	0	1	0	1	1

(b)

	3	7	5	11	10	4	2	8	9	6	1
M1	1	1	1	0	0	0	0	0	0	0	0
M3	0	1	1	1	0	0	0	0	0	0	0
M2	0	0	0	1	0	1	1	1	1	1	1
M5	0	0	0	1	1	1	1	1	0	0	1
M4	1	0	1	0	1	1	1	1	1	1	0
M6	0	0	0	0	0	0	1	1	1	0	1

(c)

Figure 37: (a) Problem given in literature (b) Best solution in literature (c) Output of the model solution along with the arrangement of parts and machines(Won, Youkyung; Kim, 1997)

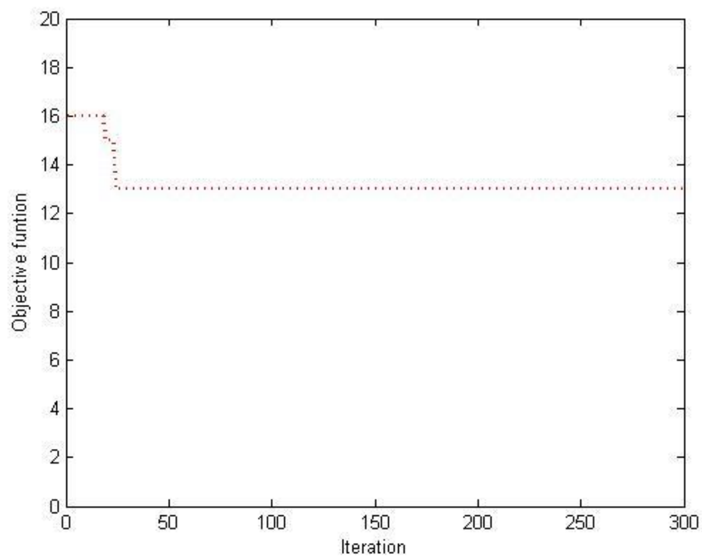

Figure 38: Graph of convergence

Test for IM Example No. 4

This IM is also one of the examples for this thesis. Figure 39 shows the output for this DSM and figure 40 shows the convergence graph of the different solutions.

The function value calculated for both the solutions are

Minimize F (output of the model solution) = 91

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
M1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	0
M2	0	0	0	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0	0
M3	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1
M4	1	1	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0
M5	1	1	0	0	0	0	0	0	0	0	0	0	1	0	0	1	1	1	0
M6	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M7	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

(a)

	1	10	4	8	7	11	9	17	18	12	15	19	5	14	16	3	2	6	13
M3	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	1	0	0
M4	1	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	1	1	0
M2	0	1	0	0	0	1	1	0	0	1	0	0	0	0	0	0	0	0	1
M6	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0
M7	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
M1	0	0	0	0	0	0	0	1	1	0	1	0	0	1	1	0	0	0	0
M5	1	0	0	0	0	0	0	1	1	0	0	0	0	0	1	0	1	0	1

(b)

Figure 39: (a) Problem given in literature (b) Output of model solution along with the arrangement of parts and machines(Wu, Tai-Hsi; Chung, Shu-Hsing; Chang, 2009)

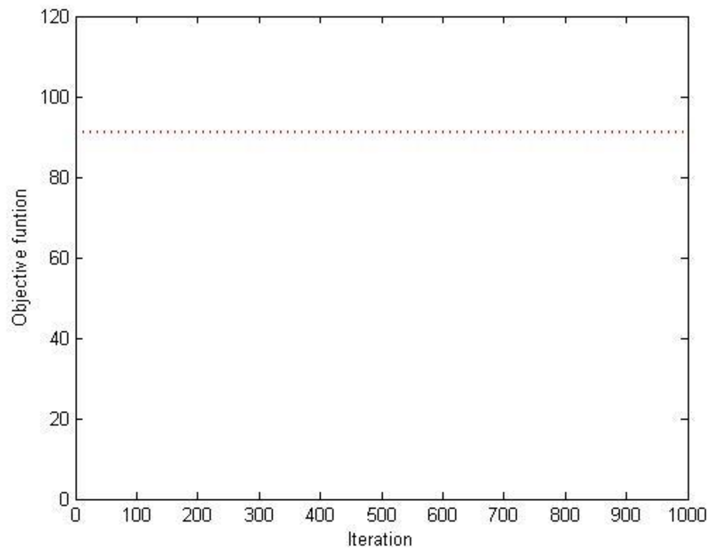

Figure 40: Graph of convergence

The examples presented below reflect the core aim of this thesis is the main case studies that are being analyzed. Until now, either the DSM or the IM have been solved and analyzed individually. When the DSM is being analyzed, the IM is taken as 0 as only the parts are taken into considerations and the interactions and the formation of modules are being highlighted. Similarly, when the IM is being taken into consideration, the DSM is taken as 0 as only the formation of cells is being looked at and not the interaction between the parts and components. For the next case studies, both the formation of modules and cells are being clustered simultaneously, it is important that the number of cells and modules remain the same in both the matrices. Due to these additional constraints on the model, the solutions obtained are not as good as the ones obtained when they are being clustered separately.

Test for DSM & IM Example No. 1

Figure 41 shows the clustered DSM from Figure and IM together where the IM has been taken from (Wu, Tai-Hsi; Chung, Shu-Hsing; Chang, 2009). Figure 42 shows the convergence graph of all the iterations.

The function value for both DSM and IM

Minimize F (best solution in literature) = 59.5

Minimize F (output of the model solution) = 54

	11	13	9	15	14	5	4	12	3	7	8	10	2	6	1
11	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
9	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	1	1	0	0	0	1	1	0	0	0	1	0
14	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	1	1	0	0	1	1	0	0	0	0
4	0	0	0	0	0	1	1	0	0	1	0	0	1	0	0
12	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
3	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0
7	0	0	0	1	0	1	1	0	0	1	1	0	0	0	0
8	0	0	0	0	0	1	0	0	0	1	1	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
2	0	0	0	0	0	0	1	0	0	0	0	0	1	0	1
6	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0
1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1

(a)

M6	0	1	0	0	0	0	0	0	0	1	0	0	1	0	0
M1	1	1	0	1	0	1	0	0	0	0	1	0	0	0	1
M3	1	1	1	0	0	0	1	0	0	0	1	0	0	1	0
M9	0	0	0	0	1	0	1	1	0	1	1	0	0	0	0
M10	1	1	0	1	0	1	0	0	1	1	0	0	1	0	0
M2	0	0	0	1	0	0	1	0	0	1	0	0	0	0	0
M5	1	0	1	0	1	1	0	0	0	0	1	0	0	0	0
M8	0	0	1	1	0	0	0	0	0	1	0	0	1	0	0
M7	0	0	0	0	0	0	1	1	0	0	0	1	0	1	0
M4	0	0	0	1	0	0	1	0	0	0	0	0	1	0	1

(b)

Figure 41: (a) DSM obtained from model solution (b) IM obtained from model solution along with the arrangement of parts and machines

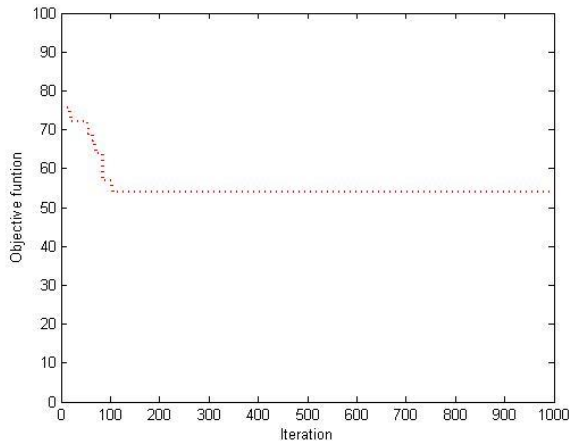

Figure 42: Graph of convergence

Test for DSM & IM Example No. 2

Figure 43 shows the DSM and IM which have been taken from (Wu, Tai-Hsi; Chung, Shu-Hsing; Chang, 2009) being clustered simultaneously and the convergence graph is shown in Figure 44.

The function value for both DSM and IM

Minimize F (output of the model solution) = 178.5

	13	9	19	7	1	4	18	5	2	6	11	10	15	14	8	3	16	17	12
13	1	0	0	0	0	1	0	0	1	1	1	0	0	0	0	0	0	0	0
9	0	1	0	0	0	0	0	0	0	0	0	1	0	0	1	1	0	0	0
19	0	0	1	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0
7	0	0	0	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	1
1	0	0	0	1	1	0	1	0	1	0	0	1	1	0	1	1	1	1	1
4	1	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0
18	0	0	0	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	1	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0
2	1	0	1	0	1	1	0	1	1	1	1	0	0	0	0	0	0	0	0
6	1	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0
11	1	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0
10	0	1	0	0	1	0	0	0	0	0	0	1	0	0	1	0	0	0	0
15	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0
8	0	1	0	0	1	0	0	0	0	0	0	1	0	0	1	0	0	0	0
3	0	1	0	0	1	0	0	0	0	0	0	0	0	1	0	1	0	0	0
16	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0
17	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0
12	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1

(a)

M5	1	0	0	0	1	0	1	0	1	0	0	0	0	0	0	0	1	1	0
M6	0	0	0	0	1	1	0	0	1	0	0	0	0	0	0	1	0	0	0
M1	0	0	0	0	0	0	1	0	0	0	0	0	1	1	0	0	1	1	0
M4	0	0	0	1	1	0	0	0	1	1	0	0	0	0	1	0	0	0	0
M2	1	1	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	1
M3	0	0	1	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0
M7	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0

(b)

Figure 43: (a) DSM obtained from model solution (b) IM obtained from model solution along with the arrangement of parts and machines

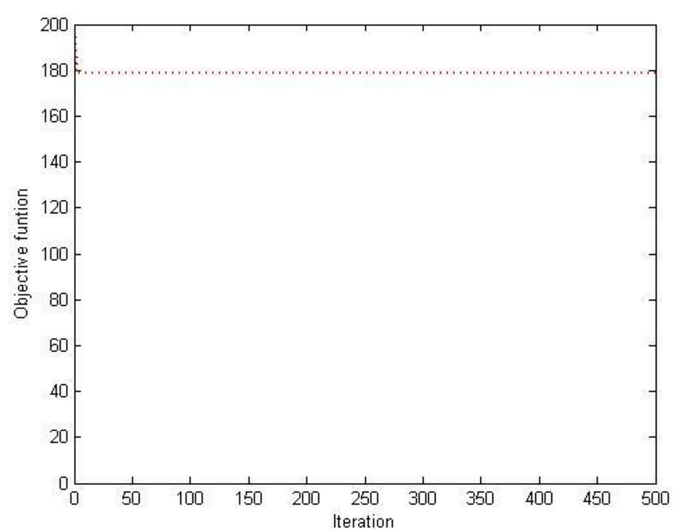

Figure 44: Graph of convergence

The tables below show a gist of all the examples that have been taken from literature and also the results from the case study that has been selected for this thesis. From Table 1, it is clear that the clustered matrices from literature showed good and sometimes even better solutions when the DSM and IM were solved individually.

Table 1: Summary of all the examples

Example Number	Best solution in literature	Output of the model solution	Number of 1's	Number of 0's
DSM 1	12	10	37	188
DSM 2	4	4	20	16
DSM 3	158	186	256	1188
DSM4	N/A	34	75	286
IM1	5	6	25	55
IM2	0	0	12	13
IM3	13	13	31	35
IM4	N/A	91	30	103

Table 2: Summary of case studies selected for testing in thesis

Example Number	Best solution in literature	Output of the model solution
DSM & IM Example 1	59.5	54
DSM & IM Example 2	N/A	178.5

While the case studies in Table 2, which consisted of both the DSM and the IM showed feasible solutions, they were not better than the ones obtained in literature. The reason is because since they are put together, a lot of constraints are forces on them in order for them to give a feasible output. What this means is that, the number of modules and cells are fixed for both the DSM and IM. This helps give a solution which is clear and ready to be applied in any manufacturing plant with the optimal part interactions and part and machine routings.

CHAPTER 5

CONCLUSIONS

The approach and method that has been presented in this thesis has helped bridge the gap between the two different domains that are manufacturing and design. The binary matrices are subject to a lot of mathematical functions which helps give the best output.

Until now, researchers and scientists have been exploring ways to combine the fields together. This approach can help build a product with the best possible techniques as it saves time and money. The resources that are invested in creating a product in terms of manufacturing as well as design individually are far too many and this can be reduced greatly. The results presented above show clearly how the DSM and IM work when they are clustered separately and how they have better results when put together.

The present work is applied to smaller to medium sized problems with average sized matrices without any problem. However, it can also handle larger matrices as the iteration used in the Genetic Algorithm is very large and it can process the results fast.

This method with the use of Genetic Algorithm can greatly pave the way to future possibilities when a product is made by fusing the manufacturing domain consisting of all the various machines and processes required with the design domain which consists of part modules that have similarities within them. It can help reduce the setup times for the process, decrease costs, minimize the use of the manufacturing floor, reduce the use of resources and most importantly help the customers be able to customize their products to their likings. This will also help the industries largely in being able to manage the huge varieties and demands in today’s world.

The future work on this approach can be in terms of subjecting non-binary matrices to the present mathematical function. Not all matrices are binary in form; some have numbers to represent the intensity and strength of the dependency while some have colors. This approach will work even if the matrix is not binary as the clustering vectors and permutation matrices being used are binary and they will just help in the movement and shuffling of the parts.

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